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AN EXTRAORDINARY RAINFALL CENTERED AT HALLETT, OKLA.

GEORGE A. LOTT

Hydrologic Services Division, U. S. Weather Bureau,[1] Washington, D. C.

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INTRODUCTION

The Hallett, Okla., storm of September 4, 1940, was the most intense rainstorm considering depth, duration, and area ever observed in Oklahoma. It has been exceeded by but few heavy rainstorms of record in the United States. Official rainfall measurements of up to 15½ inches and bucket survey totals of 24 inches were recorded. Almost all rain fell within a 9-hour period. Because of its intensity property damage was very great [1]. Figure 1 shows a generalized isohyetal pattern for the total storm period, and figure 2 the depth-duration-area curves.

The storm is one of a group in which little in the way of clues to the intense rainfall can be derived easily from the surface weather map. No surface low, pronounced pressure fall, or surface temperature discontinuity is

[1] In cooperation with the Corps of Engineers, Department of the Army.

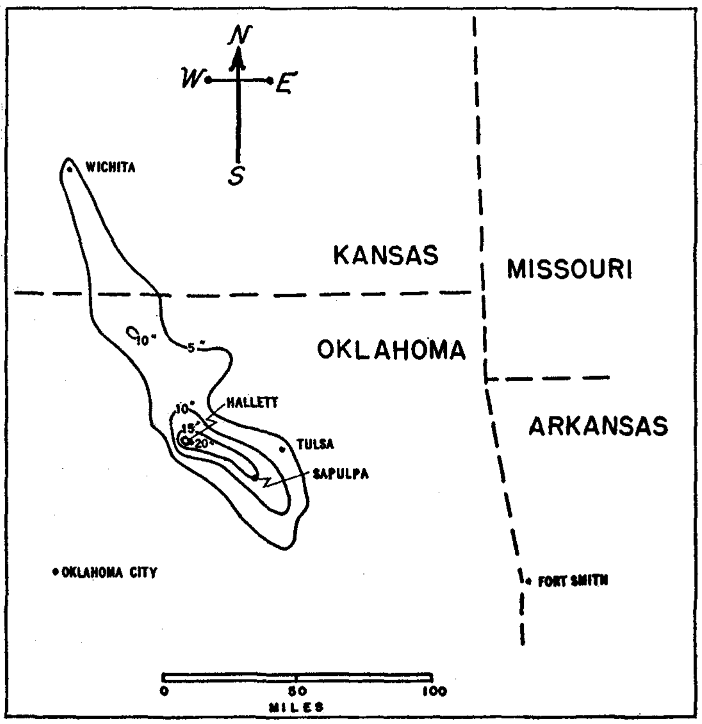

FIGURE 1.—Total rainfall for the Hallett, Okla., storm. Almost all rain fell between 0200 and 1100 CST, September 4, 1940. Note the orientation of the isohyetal pattern. The rain area progressed *in time from the northwest to the southeast.*

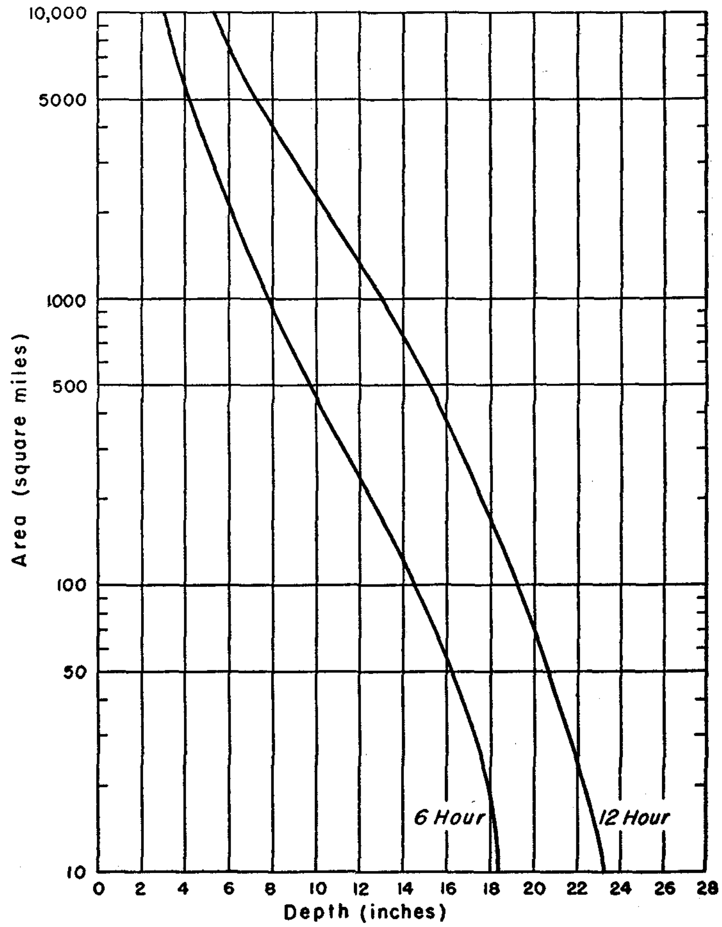

FIGURE 2.—Depth-duration-area curves for the Hallett, Okla., storm, September 4, 1940.

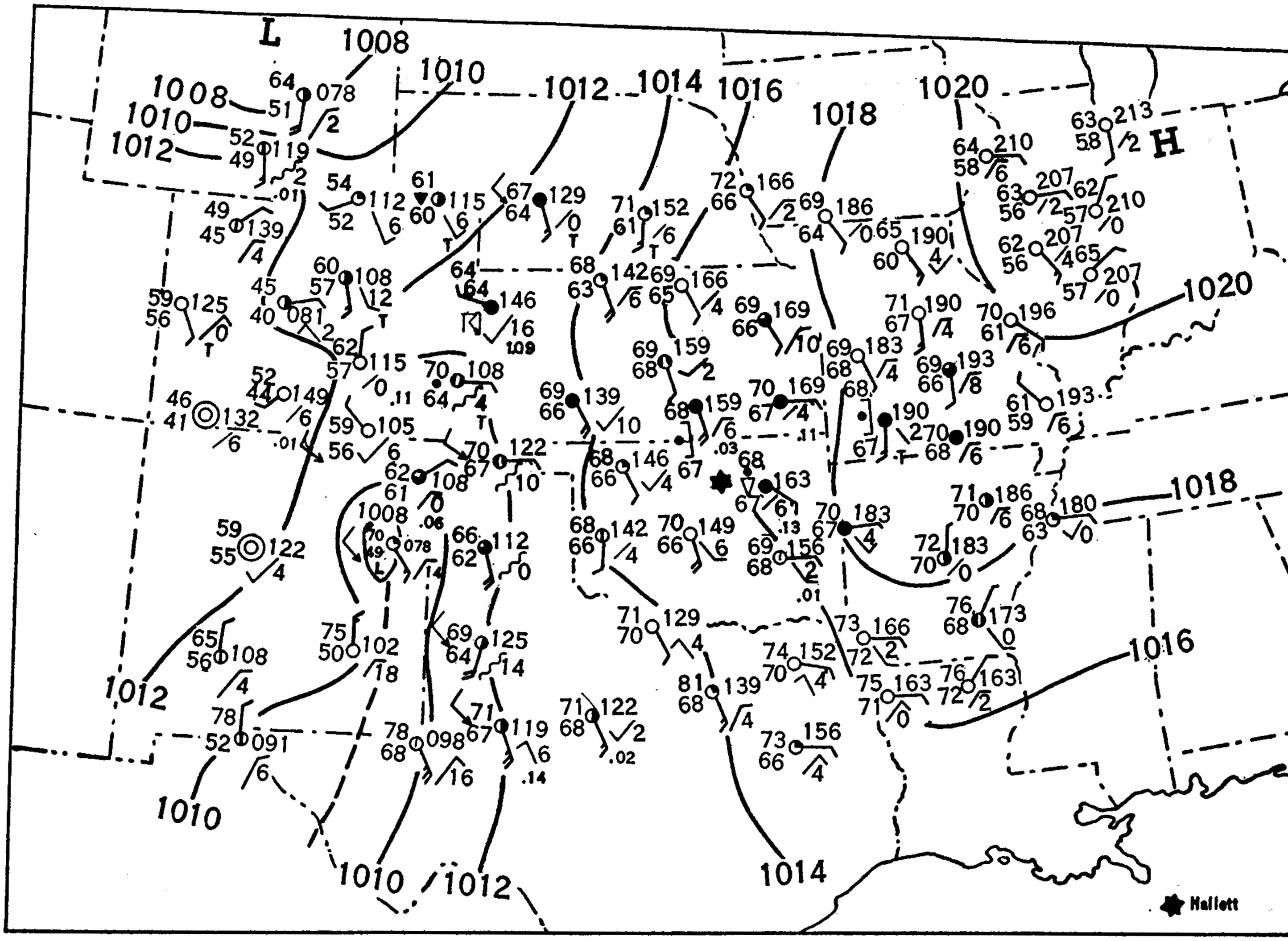

FIGURE 3.—Surface weather map for 0130 EST, September 4, 1940. Most intense rain in Oklahoma started 3 hours after this map time.

revealed by the usual macro-analytic techniques. Figure 3 shows the surface map 3 hours before heavy rain started. The storm seems to have had none of the usual extratropical cyclonic rainfall characteristics nor did it originate as a tropical storm.

This paper presents the main results of a detailed synoptic study of the storm. From the study it appears that a significant role was played by the low-level wind and temperature fields [2] and their action as a trigger mechanism that determined the temporal and geographical position of the release of energy represented by conditional instability. An explanation is suggested for the unusual orientation of the isohyetal pattern and for the rainfall progression.

SURFACE CONDITIONS PRIOR TO THE RAINSTORM

Figures 4, 5, 6, and 7 illustrate the general synoptic conditions that preceded the Hallett storm. The fronts at the surface were weak and their positions on the maps are merely suggested. The air mass between the two fronts shown on figure 4 was of Pacific origin, while the air mass coming into the United States from the north was of polar continental origin. Differences between these two air mass types is small during summer, and the very slow southeastward drift in this case no doubt increased the similarity.

Although surface properties were almost identical, a change in air mass can be detected by comparing successive 24-hour soundings. Figure 8 shows the change at Nashville, Tenn., from September 1 to September 2. A cooling of 3° to 4° C. occurred below the 840-mb. level, while moisture was almost constant. Considerable drying occurred above this level due to the high level subsiding character of the newer high.

Figures 9, 10, and 11 are 500-meter charts at 24-hour intervals which show more clearly the influx of cooler air at the lower levels. A rather pronounced trough is seen on figure 9 just south of Memphis with cold air advection indicated over the area from western Tennessee northward.

[2] This result is in accord with findings of Gilman [2] who has given a detailed discussion of the role of the wind and temperature fields (advection) in the development of atmospheric disturbances.

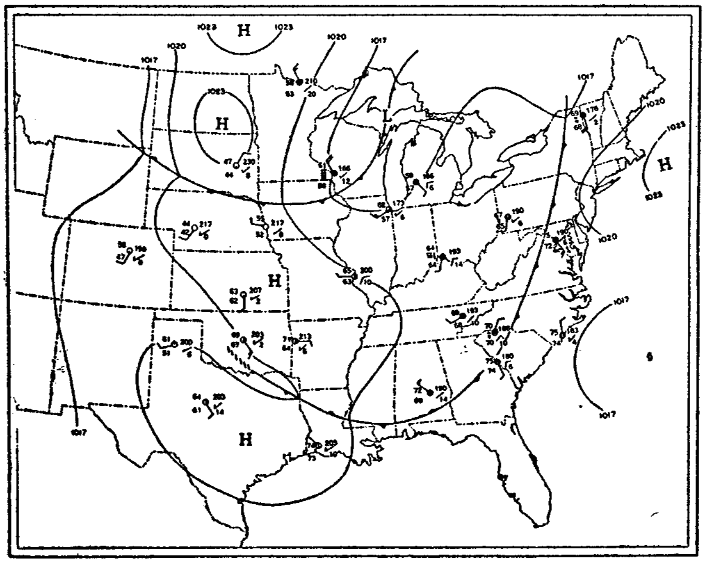

FIGURE 4.—Surface weather map for 0730 EST, August 31, 1940. This map and those in figures 5, 6, and 7 show the synoptic conditions which led up to the storm.

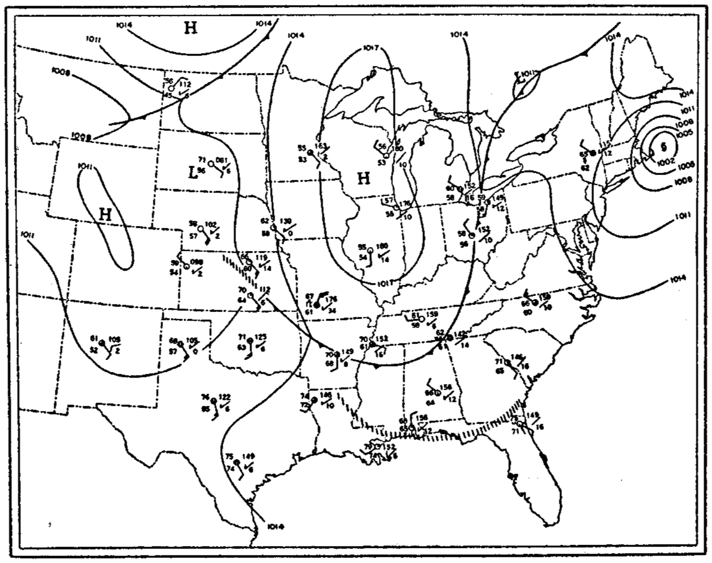

FIGURE 6.—Surface weather map for 0730 EST, September 2, 1940.

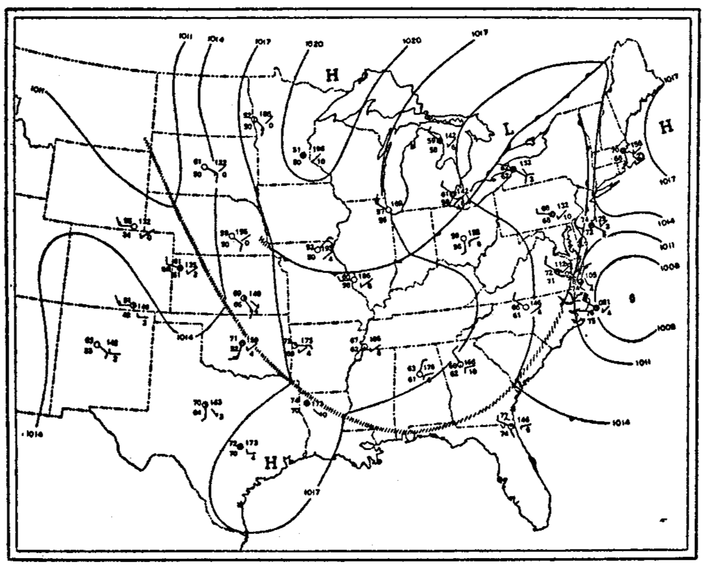

FIGURE 5.—Surface weather map for 0730 EST, September 1, 1940.

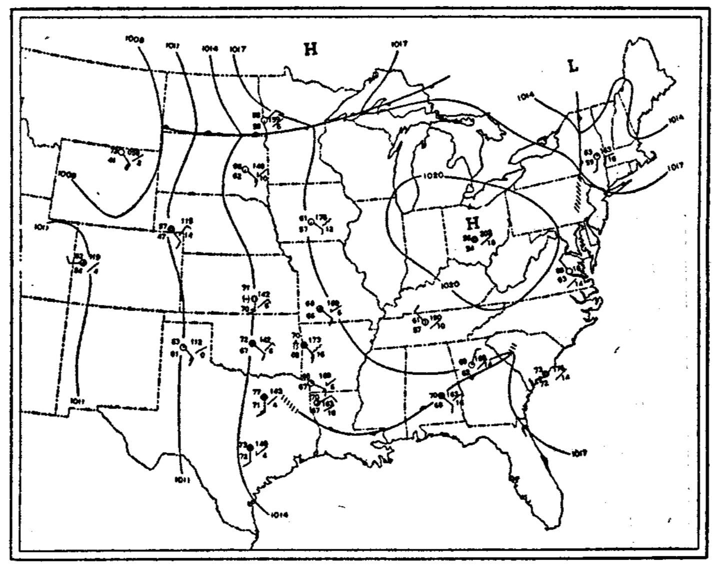

FIGURE 7.—Surface weather map for 0730 EST, September 3, 1940.

Twenty-four hours later (fig. 10) the cooler air had moved into southern Arkansas and adjacent regions, while on figure 11, the map a few hours before storm time, the cooler air is seen to have moved into Oklahoma. On figure 11 is plotted the 48-hour trajectory going upstream from Oklahoma City at 500 meters (based on wind observations) for the period ending at 0100 EST September 4, 1940. Figure 12, the soundings at Oklahoma City for 0100 EST September 3 and 4, indicates the air mass change in the lowest layers.

Twenty-four-hour surface temperature-change maps for the 4 days prior to the storm are shown in figures 13, 14, and 15. Movement of the forward portion of the cooler air mass can be traced by these temperature changes. The track of the center of temperature fall follows rather closely the trajectory of the air computed on the 500 meter charts. The possibility that these changes may have been due to differences solely in cloud cover may be discounted. At some stations this effect may have distorted the picture somewhat but in most instances, notably in the changes from September 2 to September 3 (fig. 14) a generally clear sky condition on the night of the 2d gave way to a cloudy condition the following night in the same area that surface temperatures lowered 4° to 8° F. On the following map (fig. 15) the area of temperature fall is centered over Oklahoma. All stations for which changes are plotted, with the exception of Oklahoma City, reported some cloudiness on both nights. Oklahoma City itself reported middle broken clouds at 0130 EST on the 3d while clear conditions prevailed at 0130 EST on the 4th.

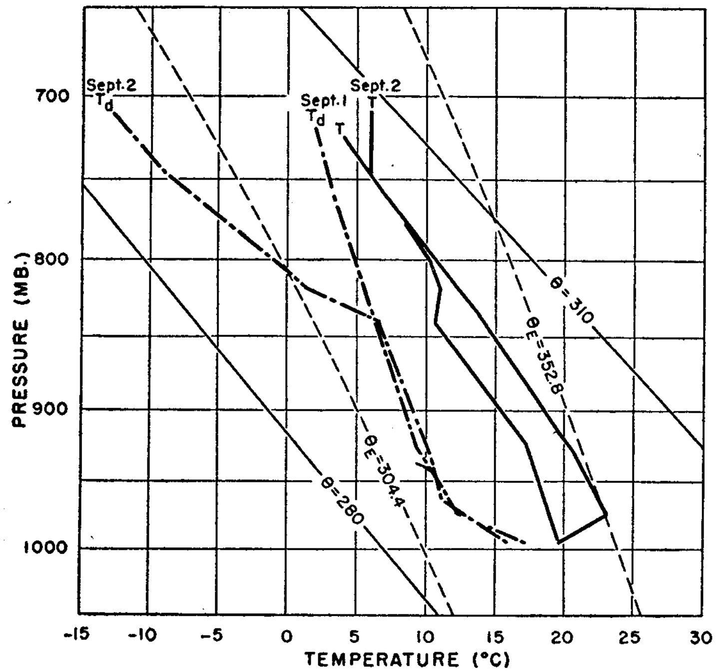

Figure 8.—Upper-air temperature (T) and dew point (T_d) soundings at Nashville, Tenn.: 0100 EST, September 1, 1940 and 0100 EST, September 2, 1940. Note the cooling in lower levels from September 1 to September 2.

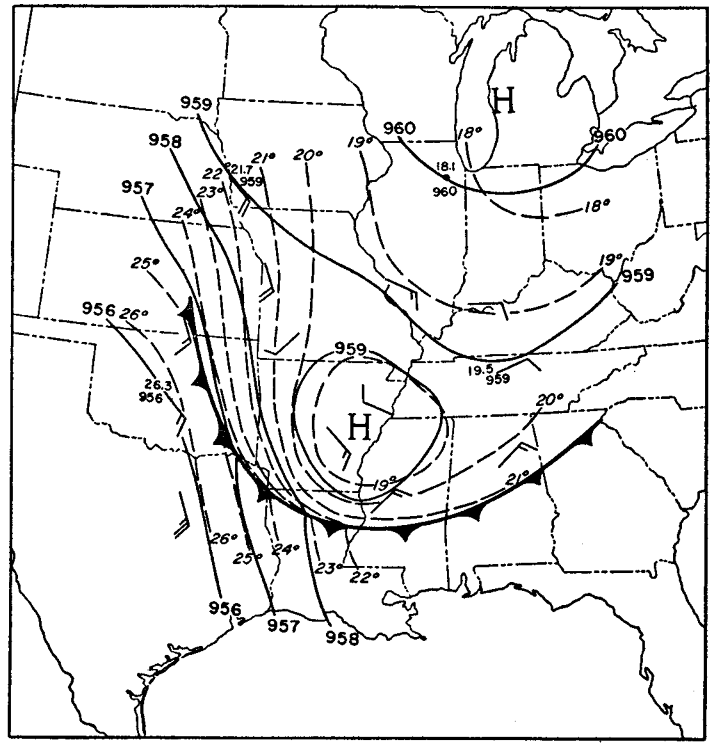

Figure 10.—500-meter chart showing isobars and isotherms for 0100 EST, September 3, 1940, and winds for 2300 EST, September 2.

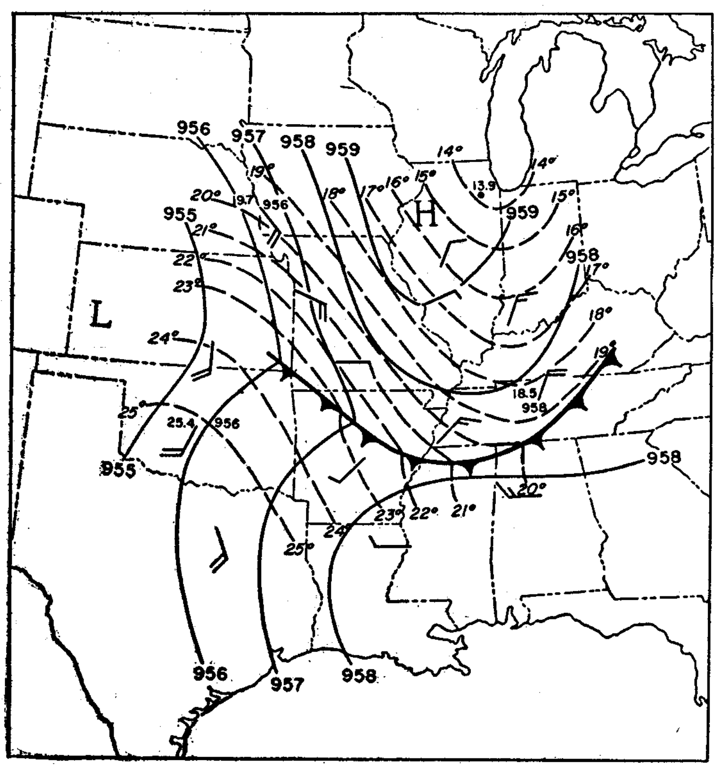

Figure 9.—500-meter chart showing isobars (solid lines, labeled in millibars) and isotherms (dashed lines, °C) for 0100 EST, September 2, 1940, and winds for 2300 EST, September 1. Compare with figures 10 and 11 to see movement of cooler air from the east.

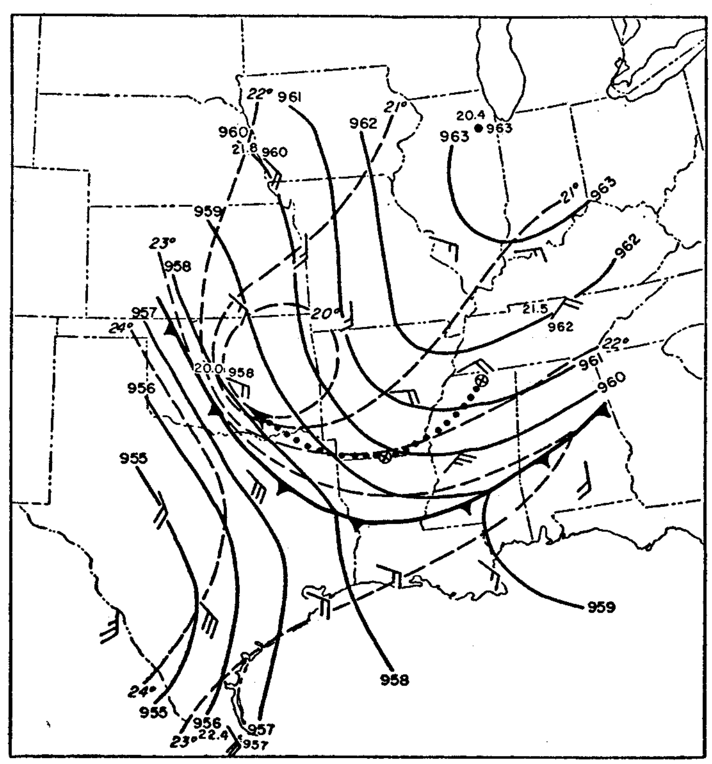

Figure 11.—500-meter chart showing isobars and isotherms for 0100 EST, September 4, 1940, and winds for 2300 EST, September 3. The dotted line is the upstream air trajectory from Oklahoma City based on wind observations for the 48-hour period ending at this map time.

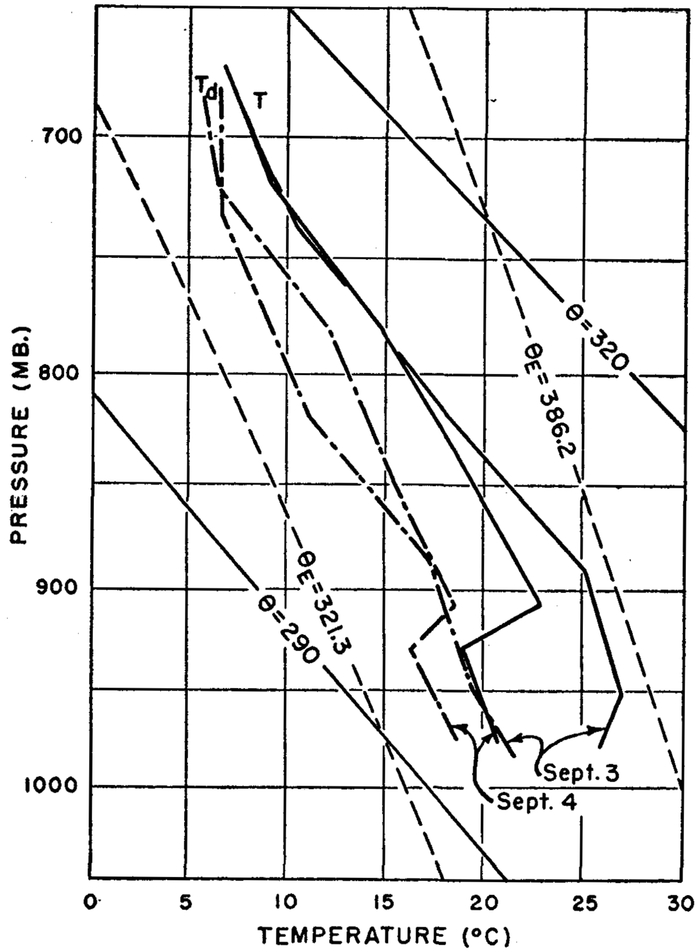

FIGURE 12.—Upper-air temperature (T) and dew point (T_d) soundings at Oklahoma City, Okla.: 0100 EST, September 3, 1940 and 0100 EST, September 4, 1940. Note the cooling in lower levels from September 3 to September 4.

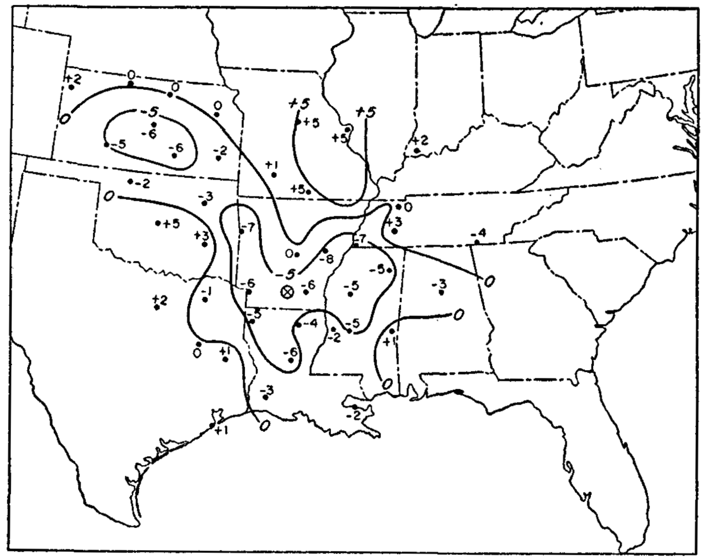

FIGURE 14.—24-hour surface temperature change (° F.) from 0130 EST, September 2 to 0130 EST, September 3, 1940.

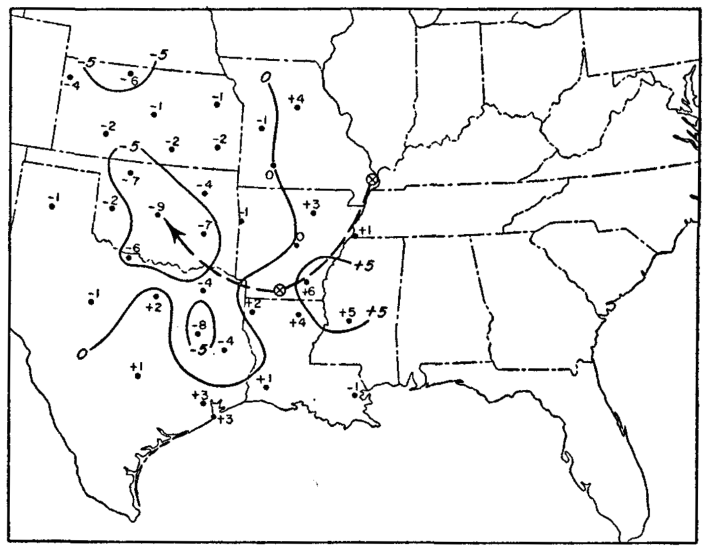

FIGURE 15.—24-hour surface temperature change (° F.) from 0100 EST, September 3 to 0100 EST, September 4, 1940. The track of the center of 24-hour temperature fall for the period covered by figures 13, 14, and 15 is shown by dashed arrow.

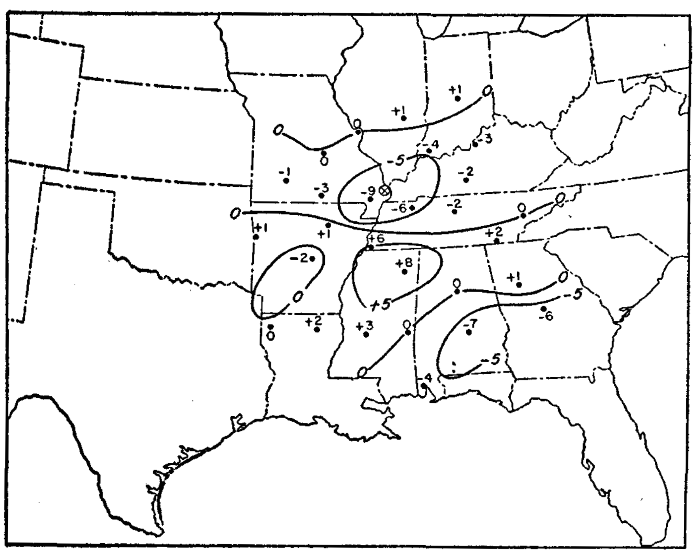

FIGURE 13.—24-hour surface temperature change (° F.) from 0130 EST, September 1 to 0130 EST, September 2, 1940. Compare with figures 14 and 15.

UPPER AIR SOUNDINGS AT OKLAHOMA CITY

The upper air sounding at Oklahoma City at 0100 EST, September 3, 1940 (lower levels only shown in fig. 12), revealed the presence of very moist air up to the 300-mb. level. Conditional instability of the real latent type was present to a noticeable degree. No large-scale rains occurred on that night.

On the following night (0100 EST, September 4) however, the Oklahoma City sounding (fig. 16) showed that drier air had moved in aloft over the moist southerly current. Above the 530-mb. level convectively stable air was then present, but real latent conditional instability was present below this level to about the same degree as at

0100 EST, September 3. In general, between 600 and 800 mb. little change occurred, but as already mentioned considerable cooling occurred in lower levels (see fig. 12).

From stability considerations alone, there is not much to distinguish the heavy rain night from its predecessor. Since the air mass was not uniquely unstable on the night of the storm, some other factor would seem to have been necessary for the development of this storm.

UPPER LEVEL SYNOPTIC SITUATION

Conditions at the 3-km. level are depicted in figures 17 and 18. A rather well developed trough was situated to the east of the Rockies on September 3, 1940, about 24 hours prior to the storm. On the following night the trough apparently had moved eastward to near Oklahoma City but had weakened considerably. At the 4-km. level (figs. 19 and 20), on the contrary, the trough was still well marked on the night of the storm.

At neither 3 nor 4 km. was the trough distinguished by unusual distribution of the elements. The passage of this trough at high levels may have contributed to the intensity of the storm, but it must be pointed out that troughs of similar nature are not an uncommon occurrence and the usual resultant showers are in no way comparable to the intensities recorded in the Hallett storm.

LOW LEVEL WIND FIELD

The time cross section at Oklahoma City (fig. 21) shows some features which are significant in the timing and placement of the rain burst on September 4. The sudden increase in wind speed at Oklahoma City in the layer immediately above the front on the morning of the 4th is of special interest. At 2300 EST of the 3d a marked wind shift between 1,000 and 1,500 meters was observed at Oklahoma City. This shift probably was associated with the boundary between the thin layer of cold air and the overrunning moist air from the south. Two hours later the raob showed the top of the frontal inversion at about 970 meters while 4 hours later, at 0500 EST, winds had increased at the 750-meter level to 45 m. p. h. from the south and at the 1,000-meter level to 50 m. p. h., indicating a further decrease in the thickness of the cold air. The frontal boundary at 0500 EST was about 650 meters above sea level.

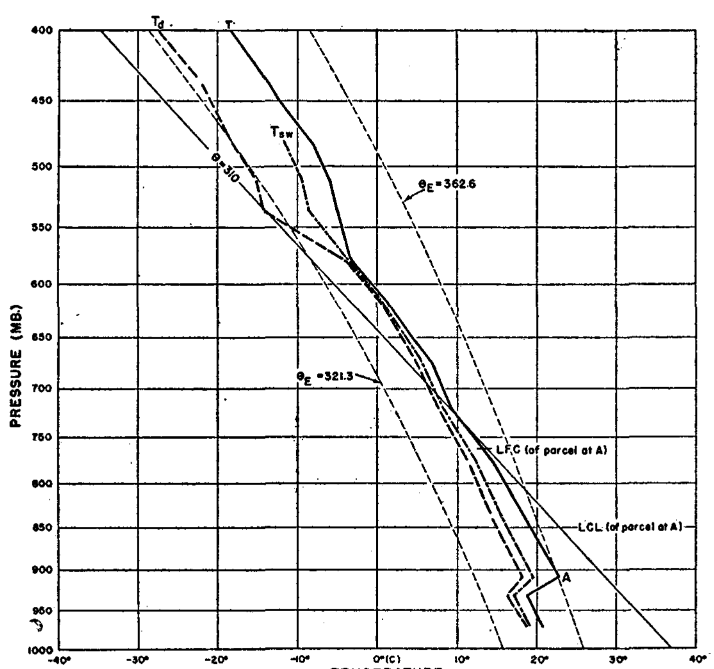

FIGURE 16.—Upper air temperature (T), dew point (T_d) and pseudo-wet bulb temperature (T_{sw}) sounding for Oklahoma City, 0100 EST, September 4, 1940. The lifting condensation level (LCL) and level of free convection (LFC) are indicated. Drier air has moved over the area above the 530-mb. level.

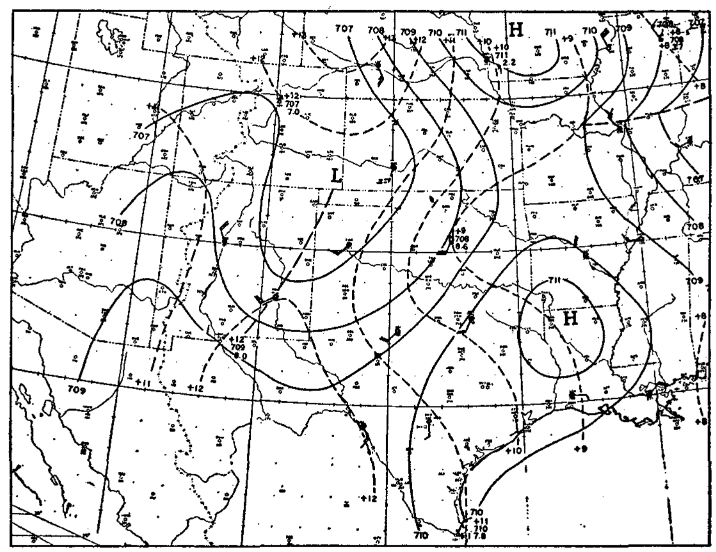

FIGURE 17.—3-km. chart showing isobars (solid lines, labeled in mb.) and isotherms (dashed lines, ° C.) for 0100 EST, and winds for 0500 EST, September 3, 1940.

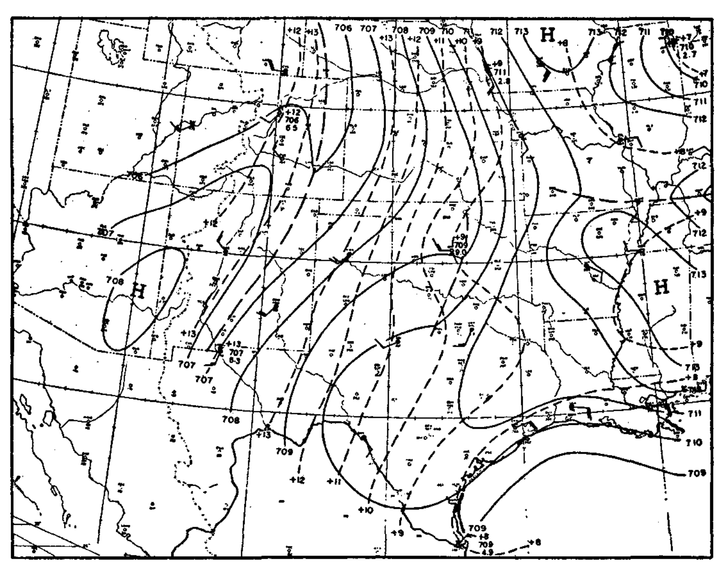

FIGURE 18.—3-km. chart showing isobars and isotherms for 0100 EST and winds for 0500 EST, September 4, 1940. Trough to east of Rockies on figure 17 has moved eastward but weakened considerably.

To explain this large increase in wind speed a series of 24-hour sea level pressure change maps was analyzed. Two can be seen in figures 22 and 23. The series shows that a weak pressure fall area was centered near 101° W. at the time of the low level strong winds (southerly jet). The area could be extrapolated back to the Pacific Coast where it had been associated with a Pacific storm, the occluded front of which hit the northern California coast on the morning of September 2. No well organized 3-hour pressure change area could be discerned in connection with this storm. The 24-hour katallobaric center moved about 12° in longitude per 24 hours with rises of 2 to 5 mb. per 24 hours both to the rear and ahead of it. It should be pointed out that the speed of the pressure fall area was about twice that of the trough aloft at 4 km., and therefore no association with this feature could be made.

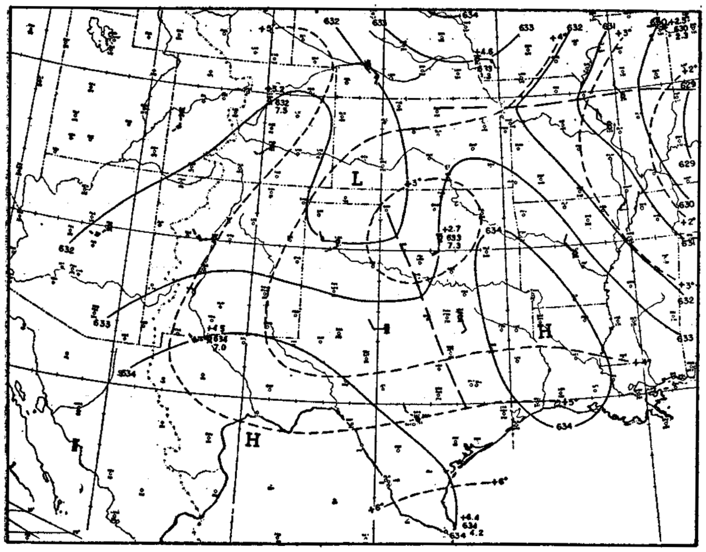

FIGURE 19.—4-km. chart showing isobars (solid lines labeled in mb.) and isotherms (dashed lines, ° C.) for 0100 EST, and winds for 0500 EST, September 3, 1940.

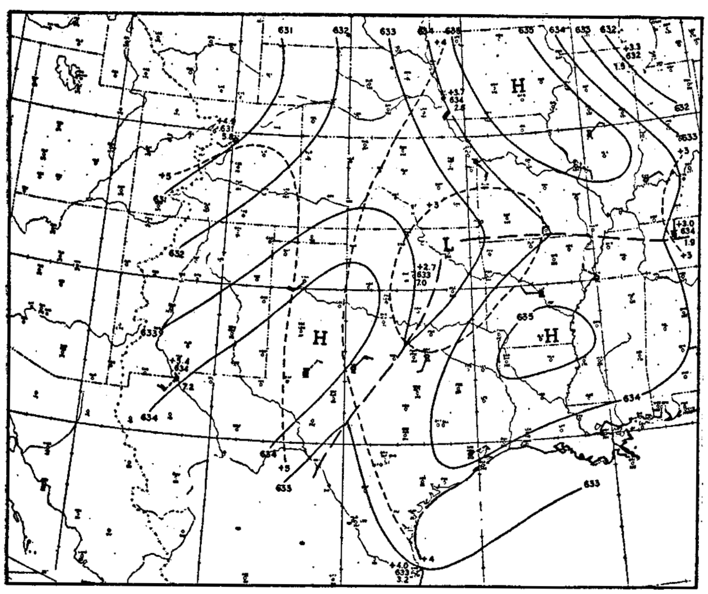

FIGURE 20.—4-km. chart showing isobars and isotherms for 0100 EST and winds for 0500 EST, September 4, 1940. Trough to east of Rockies which weakened at 3 km. as shown in figures 17 and 18 is still well marked at 4 km. just before the rain began.

To test whether this pressure fall area was in fact associated with the increase in southerly winds at low levels, the Amarillo upper winds (not shown) were examined. These showed a marked increase (from a previous velocity of 20 m. p. h. to a velocity of 40 m. p. h. from the south) at the 2300 EST observation of the 3d at 900 meters above the surface. This was 6 hours before the high wind of 50 m. p. h. at 600 meters above the surface at Oklahoma City. It might be well to point out that only a small part of this increase could be attributed to a normal diurnal variation in wind speed.

The time cross-section (fig. 21) for Oklahoma City shows an increase in wind speed of about 5 m. p. h. through the lowest 2,500 meters between the 1700 EST observation and the 2300 EST observation on the 3d. (The cold air was well established in the Oklahoma City area by the time of the latter wind observation.) Subsequently (at 0500 EST of the 4th) the wind increased at the 1,000-meter level about 25 m. p. h. above its value for 2300 EST, September 3. This corresponds well with the 20-m. p. h. increase recorded at Amarillo, Tex., 6 hours earlier. It may be concluded that most of the increase in wind speed at Oklahoma City was not due to the intrusion of low level cold air or the rainstorm itself, but resulted from an increased pressure gradient brought about by a fall in pressure to the west and a rise to the east of the rainfall area.

Examination of the rainfall recorder record for Wichita, Kans. (not shown), shows that the heavy rain burst occurred in a 2-hour period ending at 0700 EST of the 4th, corresponding closely to the time that the low level southerly jet was passing Oklahoma City. (Oklahoma City and Wichita are almost in a north-south line.)

The progression of rainfall from northwest (an unusual feature of this storm) may be explained by the fact that the combination of a northwest-southeast orientation of the cold air mass edge (nearly stationary then in regard to its southwest component of motion) and an eastward progression of the belt of strong southerly winds would produce an apparent movement of the rain burst from the northwest toward southeast.

Figures 24 and 25 illustrate schematically a solution to conditions that prevailed in the rather thin cold air mass at 750 meters over northeastern Oklahoma on the morning of September 4. Figure 24 shows observed conditions at 2300 EST and 0100 EST (times of upper wind and radiosonde observations). Figure 25 shows the observed winds and probable conditions of temperature at 0500 EST.

At 750 meters above sea level over Oklahoma City cold air is found at 0100 EST and warm air at 0500 EST (as judged from the time cross-section fig. 21). The wind at Oklahoma City was southeast about 25 m. p. h. at 2300 EST, but by 0500 EST it had increased to 45 m. p. h. from the south. At Kansas City no increase in wind

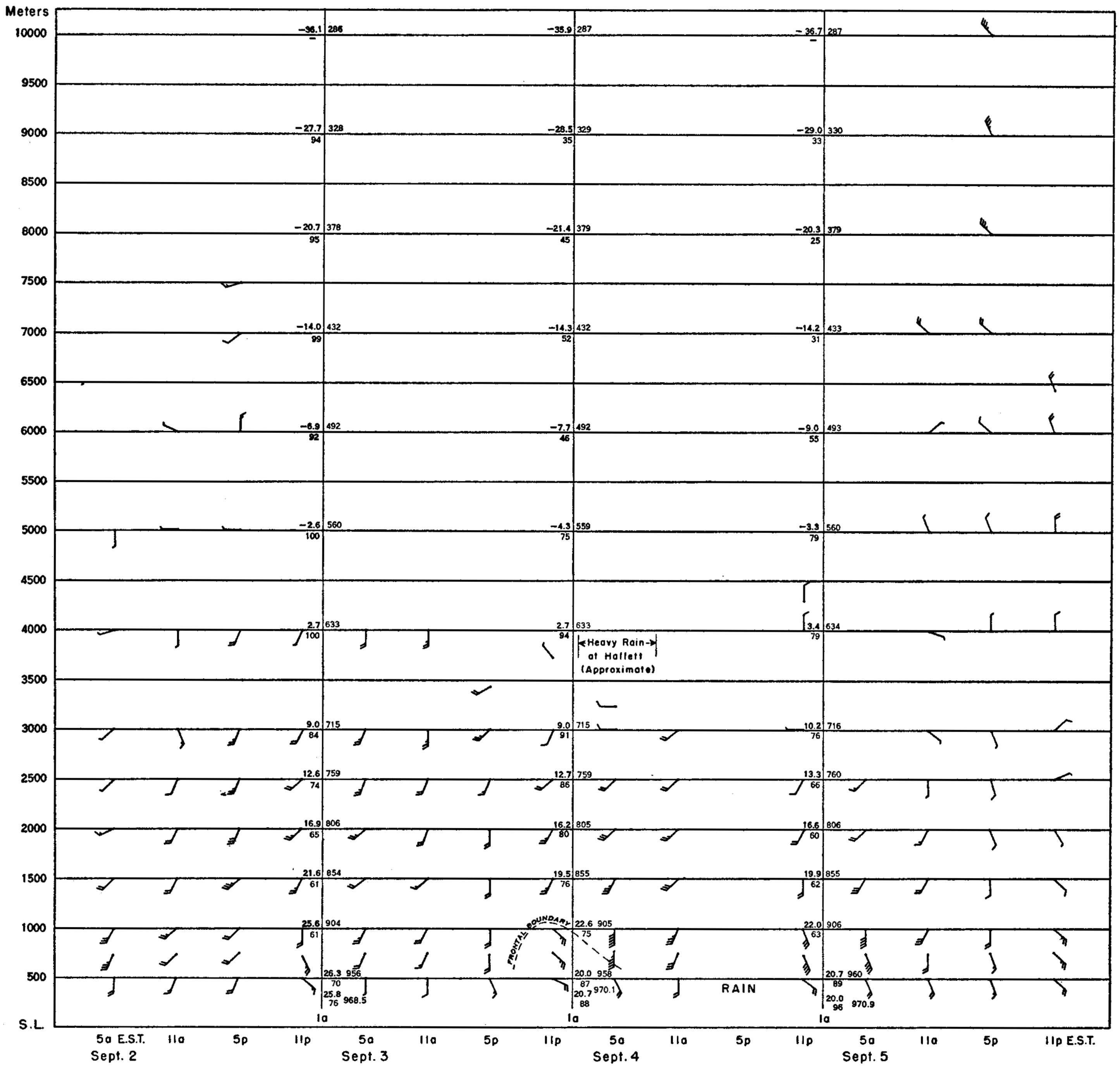

FIGURE 21.—Time cross section at Oklahoma City, Okla., September 2–5, 1940. Wind direction is plotted as if projected on horizontal chart. Half barb=5 m. p. h. and full barb=10 m. p. h. wind force. The plotted upper air data show temperature (° C., upper left), relative humidity (%, lower left), pressure (mb., right). Note the increase in wind speed and decrease in temperature in the lower levels.

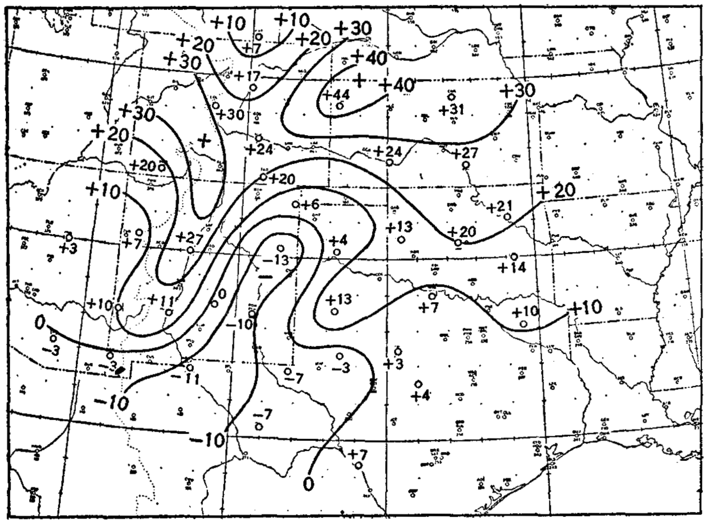

FIGURE 22.—24-hour sea level pressure change, 0130 EST, September 3 to 0130 EST, September 4, 1940. Isallobars are in tenths of millibars. Compare with figure 23 to see movement of pressure-fall area.

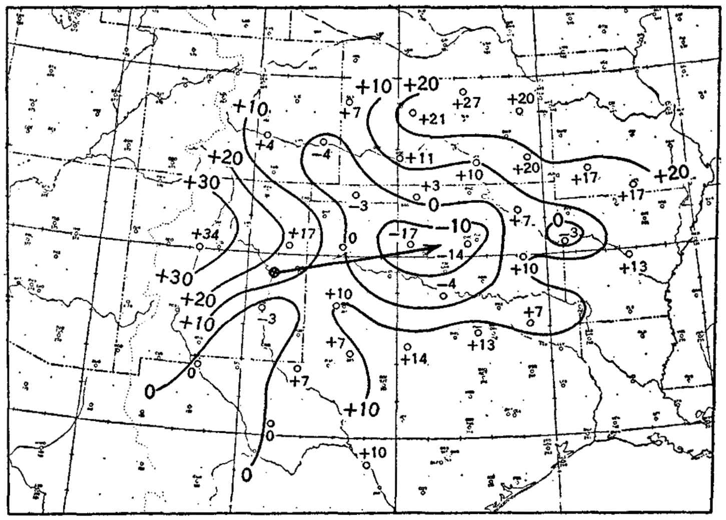

FIGURE 23.—24-hour sea level pressure change, 1330 EST, September 3 to 1330 EST, September 4, 1940. Isallobars are in tenths of millibars. Arrow indicates 12-hour movement of the pressure fall area.

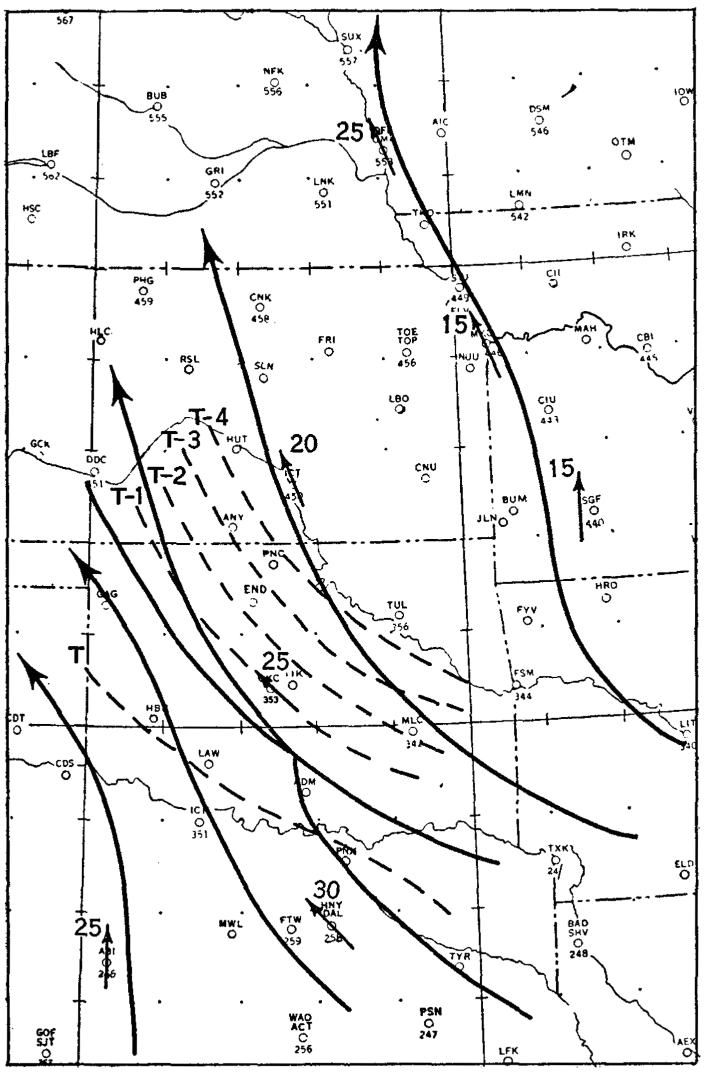

FIGURE 24.—Schematic 750-meter chart showing conditions over northeastern Oklahoma on the morning of September 4 just before the rain began. Analysis based on 2300 EST September 3 upper winds and 0100 EST September 4, 1940, radiosonde. Compare with figure 25.

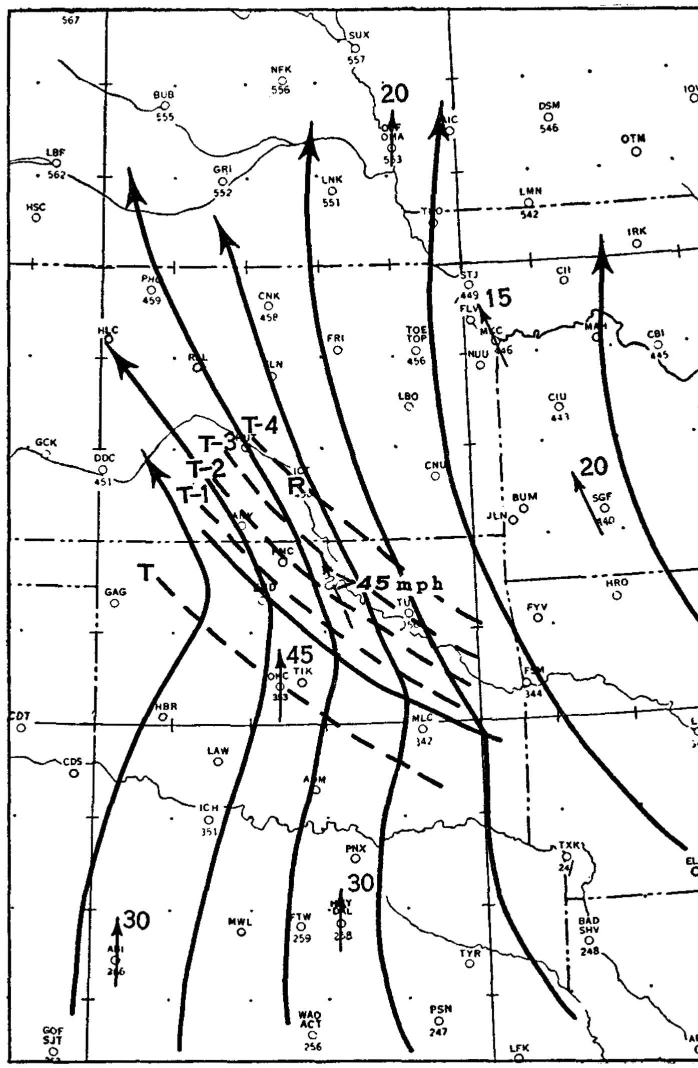

FIGURE 25.—Schematic 750-meter chart during heavy rain. Analysis based on probable temperature conditions and observed upper winds for 0500 EST September 4, 1940.

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speed had taken place, and there was no change in wind direction. This being the case, a rapid increase in speed in the cold wedge over northeastern Oklahoma must be inferred and from logical considerations the advection may be deduced. This would imply a very intense localized band of warm geostrophic advection due to the superposition of a rapid increase in wind velocity on an air mass in which a temperature gradient was present.

CONCLUSIONS

To sum up, the most plausible explanation for the Hallett storm seems to be the occurrence of three fortuitous circumstances that prevailed over northeastern Oklahoma on the morning of September 4, 1940: (1) The presence to the south and over the area of an extensive conditionally unstable air mass, (2) the intrusion of a thin layer of cold air at the surface from an easterly direction, and (3) a nearly concurrent increase of low level southerly winds as the result of an eastward moving katallobaric area associated with an old Pacific Low. The last two factors combined in such a manner as to produce a narrow low level band of intense warm geostrophic advection over the region from approximately Wichita, Kans., to Tulsa, Okla.

In general, it has been the observation of the Hydrometeorological Section of the Weather Bureau that moist conditionally unstable air, low level temperature gradient, and a strong (usually southerly) low level wind are important factors in the structure of most great rain storms. However, synoptic situations that bring about and accompany this array of conditions may vary considerably from those illustrated in this analysis of the Hallett storm.

ACKNOWLEDGMENT

The author wishes to express his thanks to Dr. C. S. Gilman for his advice in all phases of this storm study.

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2. C. S. Gilman, "An Expansion of the Thermal Theory of Pressure Changes," ScD Thesis, Massachusetts Institute of Technology, 1949 (unpublished).